

THE INTEGRAL/SPI RESPONSE AND THE CRAB OBSERVATIONS

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ABSTRACT

The Crab region was observed several times by INTEGRAL for calibration purposes. This paper aims at underlining the systematic interactions between (i) observations of this reference source, (ii) in-flight calibration of the instrumental response and (iii) the development and validation of the analysis tools of the SPI spectrometer (Vedrenne et al. 2003). It first describes the way the response is produced and how studies of the Crab spectrum lead to improvements and corrections in the initial response. Then, we present the tools which were developed to extract spectra from the SPI observation data and finally a Crab spectrum obtained with one of these methods, to show the agreement with previous experiments. We conclude with the work still ahead to understand residual uncertainties in the response.

Key words: INTEGRAL/SPI; Crab; instrumental response; calibration.

1. CRAB OBSERVATIONS

During its first year in orbit, INTEGRAL observed the Crab region (the nebula and its pulsar) twice : in February (revolutions 39-45) and August (revolutions 102-103) 2003. The total observation time yields 1,723 ks (including annealing periods), performed in different modes : on- or off-axis, in staring or dithered mode, with a 5 x 5 or an hexagonal dither pattern. Because of its high luminosity and apparent lack of variability, this source is used as a reference for the spectrometer calibration.

2. INSTRUMENTAL RESPONSE

Response decomposition The response is decomposed into IRFs and RMFs :

- the redistribution matrix files (RMFs) are divided into three components describing (1) the events of the full-energy peak, (2) the Compton events interacting first in the detectors, (3) those interacting first in the passive material. They do not depend on the direction or the detector but only on the energy.
- the image response files (IRFs) describe, for a given input photon energy, the effective area of each detector for all directions in the field of view.

Production The INTEGRAL/SPI instrument response is produced using a suite of Monte Carlo simulation software developed at NASA/GSFC based on the GEANT-3 package called MGEANT (Sturmer et al. 2003). This production also required the development of a detailed computer mass model for SPI.

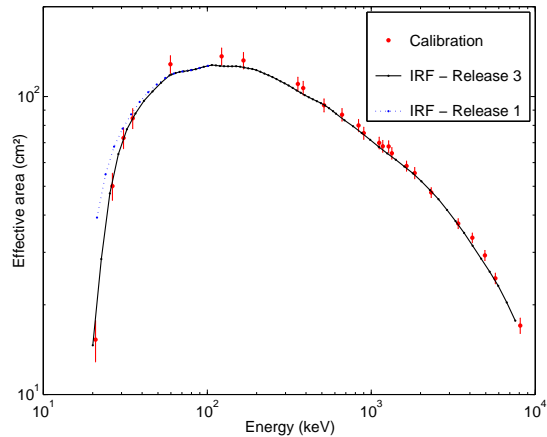


Figure 1. SPI photopeak effective area : comparison between ground calibration measurements (dots with error bars), and two successive IRF releases (dotted and plain lines).

Absolute determination of the camera photo-peak effective area was obtained from measurements (points in Fig. 1) performed just before the launch during an extensive ground calibration campaign (Attie et al. 2003; Schanne et al. 2003) of SPI in 2001 April at the Bruyères-le-Châtel (BLC) site of CEA. These measurements were compared to simulations and led to the initial release of the SPI response (Fig. 1, dotted line).

Correction Initial analysis of ground calibration data was performed only on lines with energies at or above 60 keV. After the launch, it was found through analyses of early Crab observations, that the Crab flux below these 60 keV was underestimated compared to the spectrum expected. It enabled us to point out an over-estimation of the low energy efficiency.

Additional analyses of 4 low-energy lines from the BLC data were performed. The 20.80 and 26.35 keV lines of the ^{241}Am calibration source had initially been ignored because of their low statistics. The ~ 30.8 and ~ 35.07 keV lines of ^{133}Ba , blended by the Compton component of higher energy lines, had also been rejected. A new response, corrected below 60 keV by taking into account these 4 lines, was derived (Fig. 1, plain line), without any assumption on the Crab spectrum.

3. DECONVOLUTION METHODS

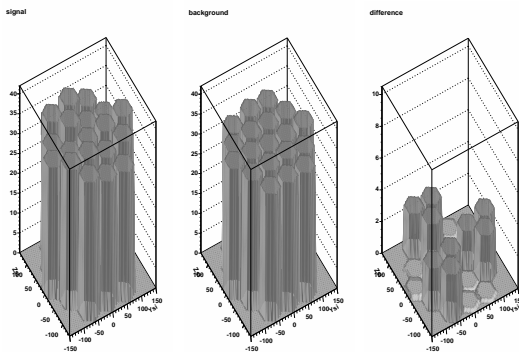


Figure 2. Count rates in the 19 Ge detectors in the 20-8000 keV band, during a Crab on axis pointing. From left to right : total count rate, estimated background count rate and their difference. The pattern of the projection of an on axis source through the mask on the detector plane, with its 120 degrees symmetry, is visible.

Several tools have been developed to extract source spectra from SPI observation data, including Spiros and XSPEC 12.

- in its spectral mode, Spiros (Skinner & Connell 2003), available in the INTEGRAL off-line

scientific analysis (OSA) distribution (<http://isdc.unige.ch/index.cgi?Soft+soft>), adjusts the intensity of sources simultaneously with the scaling factors to apply to the background model chosen. The best solution is searched for in each energy bin successively. The off-diagonal terms of the instrumental response are not taken into account in the deconvolution – all events are treated as photopeak events – and the resulting spectrum is in *pseudo-photons*. A “Spiros dedicated” redistribution matrix was derived using Monte Carlo simulations of both the SPI instrument and the *Spiros* software. This matrix can for example be used by the spectral-fitting program *XSPEC*, to fit a model to the real photon spectrum ;

- *XSPEC 12*, developed at NASA/GSFC (Shrader 2004) is a new release of *XSPEC* including SPI specific packages – to be delivered soon. While *XSPEC 11* can be used to fit a mathematical model to an already background subtracted and deconvolved SPI source spectrum, *XSPEC 12* can work directly from the individual detector spectra. Using, unlike *Spiros*, the full instrumental response – IRFs and RMFs – reconstructed for each source, it adjusts simultaneously the model parameters of each of the sources considered and the scaling factors to apply to the background model.

To account for initial discrepancies in the Crab derived flux between *Spiros* and *XSPEC 12*, a new version of the “Spiros dedicated” redistribution matrix mentioned above was recently derived at NASA/GSFC.

However, the main challenge is to properly model the background which represents a huge fraction of the total measured count rate (Fig. 3 and 3).

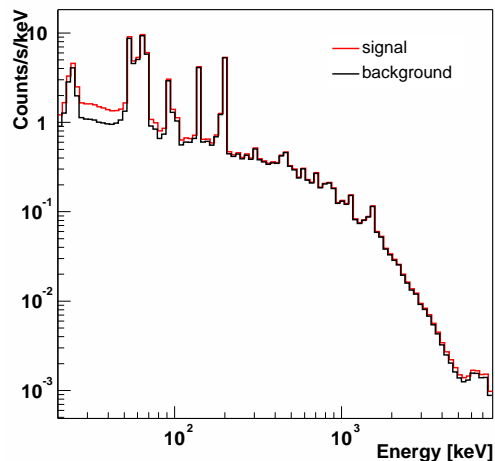


Figure 3. Total count rate (upper line) and estimated background count rate (lower line) during a Crab observation : the signal of interest represents only a tiny fraction of the total count rate.

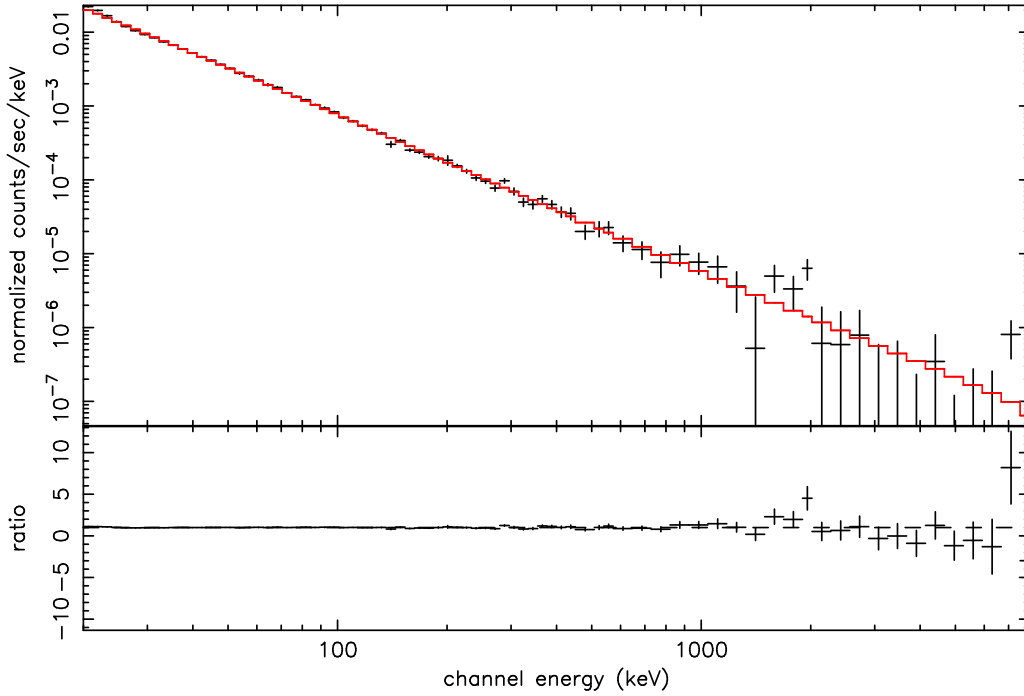


Figure 4. SPI Crab spectrum extracted from 44 NRT science windows in INTEGRAL revolution 44, using OSA 3.0 and a saturated Ge background model fitted detector by detector with Gaussian statistics.

Spectral studies of Crab and other reference sources were done with both *Spiros* and *XSPEC 12*, enabling us to cross-calibrate these tools. The resulting spectra are now consistent in shape and normalization. An initial discrepancy in normalization was reduced after a new redistribution matrix was derived for *Spiros*. Some differences remain which are still under study.

4. CRAB SPECTRUM

The Crab spectrum in Fig. 4 was extracted using as standard a method as possible, so that any scientist undertaking to analyze SPI observations shall be able to reproduce such a spectrum. It corresponds to the first 44 near real time science windows of revolution 44, performed with a 5×5 dither pattern. Distribution 3.0 of the observation analysis software (OSA) was used and the *spi_science_analysis* script was run mainly with default parameters, the most important of which concern the background : spiback produced a background model based on the count rates in saturating Ge detectors and *Spiros* adjusted the source flux and background count rates in each energy bin, assuming the time variation given by the model and computing the best detector to detector ratios.

Table 1. Flux ($\text{ph}/\text{cm}^2/\text{s}$) and power law index of total Crab gamma-ray emission.

Instrument	Index	50-100 keV flux
OSO-8	2.00 ± 0.06	$6.41 \cdot 10^{-2}$
GRIS	2.15 ± 0.03	$4.52 \cdot 10^{-2}$
CGRO/OSSE [†]	2.19 ± 0.03	$5.68 \cdot 10^{-2}$
CGRO/BATSE [†]	2.20 ± 0.01	$6.83 \cdot 10^{-2}$
SAX/PDS [†]	2.13 ± 0.01	$4.92 \cdot 10^{-2}$
INTEGRAL/SPI	$2.17 \pm 0.01^*$	$7.08 \pm 0.03^* \cdot 10^{-2}$

[†] private communication

* statistical error only

Above 1 MeV, the flux uncertainty grows up as the source flux gets smaller and the basic background model used starts to show its limits : the features visible above 1 MeV correspond to instrumental background residuals.

A power law $F(E) = K \left(\frac{E}{1 \text{ keV}} \right)^{-\alpha}$ with a spectral index $\alpha = 2.169 \pm 0.008$ and a normalization $K = 14.44 \pm 0.44 \text{ ph/cm}^2/\text{s/keV}$ fits well to the spectrum ($\chi^2/\text{d.o.f} = 1.31$) in the 40 keV to 8 MeV energy range.

Imposing the canonical photon spectral index of 2.10 found by X-ray experiments for the entire Crab, we estimate ($\chi^2/\text{d.o.f} = 2.39$) a normalization of $10.80 \pm 0.03 \text{ ph/cm}^2/\text{s/keV}$ at 1 keV, to compare with a value of $9.59 \text{ ph/cm}^2/\text{s/keV}$ given by Willingale et al. (2001).

A broken power law fits only slightly better ($\chi^2/\text{d.o.f} = 1.29$) than a single power law. Imposing a low energy index $\alpha_1 = 2.10$, we find a high energy index $\alpha_2 = 2.19 \pm 0.01$ with a break around $61 \pm 6 \text{ keV}$ and a normalization of $11.03 \pm 0.05 \text{ ph/cm}^2/\text{s/keV}$ at 1 keV.

Using a different energy range or background handling method, the fit parameters found vary slightly. Even without taking into account systematic uncertainties due to the calibration and background handling works still in progress, Table 1 shows a very good agreement between SPI and other gamma-ray experiments.

5. CONCLUSION

After a few months of fine tuning of both the instrumental response and the deconvolution tools, the Crab spectra extracted from INTEGRAL/SPI observations with the various software available are compatible with each other and rather consistent with previous experiments.

Some further work will be necessary to build more elaborate background models and become more confident in the fluxes derived. Although the response and the extraction software might still evolve in the future especially to account for the loss of detector 2, the tools available today are sufficient to study point sources observed with INTEGRAL.

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